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# RESEARCH MEMORANDUM

## INVESTIGATION OF TITANIUM CARBIDE BASE CERAMALS CONTAINING EITHER NICKEL OR COBALT FOR USE AS GAS-TURBINE BLADES

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CLASSIFICATION CANCELLED

Authority J. W. Crowley Date 12-11-53
E.O. 10501
By JH 1-7-53 See NACA
RF 1773

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
August 18, 1952

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RESEARCH MEMORANDUM

# INVESTIGATION OF TITANIUM CARBIDE BASE CERAMALS CONTAINING EITHER NICKEL OR COBALT FOR USE AS GAS-TURBINE BLADES

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## SUMMARY

The following two ceramals were investigated for use as gas-turbine blade materials: (a) 65 percent TiC plus 20 percent Co plus 15 percent (CbTaTi)C and (b) 65 percent TiC plus 20 percent Ni plus 15 percent (CbTaTi)C. Concurrently, the effectiveness of a number of methods of preventing ceramal-blade-root failure was studied. Ceramal blades were run at temperatures of 1500° to 1900° F and at speeds of 10,000 to 26,000 rpm. The endurance characteristics of these blades were compared with Stellite 21 and S-816 alloy blades of identical airfoil configuration. Prior to the blade evaluation, physical-property evaluations of the ceramals were made.

The results of the investigation are as follows:

(a) Two TiC plus Co plus (CbTaTi)C blades ran 78 and 111 hours at 1500° to 1900° F and survived 94 and 95 percent, respectively, of a 136-blade Stellite 21 alloy sample. The wheel speed was 10,000 to 15,000 rpm. A TiC plus Ni plus (CbTaTi)C blade ran 99 hours at 1500° F and 25 hours at 1700° F without failure, during which time 100 percent each of a 10-blade Stellite 21 alloy sample and a 3-blade S-816 alloy sample failed. The remaining 18 ceramal blades investigated yielded poor results as compared with their respective alloy control blades.

(b) The use of platinum, copper, or nickel plate on the base of the ceramal blades was effective in extending blade-root life; platinum appeared most effective.

(c) The average short-time tensile strengths of an 80 percent TiC plus 20 percent Co ceramal at 1800° and 2200° F were slightly greater than those for the 65 percent TiC plus 20 percent Co plus 15 percent (CbTaTi)C ceramal. The use of nickel rather than cobalt in the TiC plus (CbTaTi)C ceramal produced significant reductions in the average modulus of rupture strengths at 1800°, 2000°, and 2200° F and a slight reduction at 2400° F. The thermal-shock resistance of the TiC plus Co ceramal was better than that of the TiC plus Co plus (CbTaTi)C ceramal, which in turn was better than that of the TiC plus Ni plus (CbTaTi) ceramal.

[redacted] 

(d) The use of a solid solution of the mixed carbides of Ta, Ti, and Cb, in the TiC plus Co and the TiC plus Ni ceramal blades inhibited oxidation during operation.

## INTRODUCTION

Ceramals are currently being studied for use as gas-turbine blade materials. An investigation of an 80 percent titanium carbide TiC plus 20 percent cobalt Co ceramal (reference 1) indicated that this composition possessed potentialities as a gas-turbine blade material, 2515
but was limited by a susceptibility to oxidation and by brittleness. The addition of ~~a~~ solid solution of the mixed carbides of tantalum Ta, titanium Ti, and columbium Cb has been found to improve the oxidation resistance of this ceramal approximately tenfold (reference 2); it therefore appears that the oxidation of this ceramal, and possibly of other TiC base ceramals, can be inhibited and that the brittle nature of this ceramal probably is the primary obstacle limiting its use as a gas-turbine blade material.

The object of this investigation was to determine the life of gas-turbine blades made of TiC ceramals containing either nickel Ni or Co and modified by the addition of the solid solution of the mixed carbides of titanium, tantalum, and columbium. It was anticipated that these materials would be brittle and that stress-concentration effects in the root and consequent failure there would result; a number of methods of minimizing the possibility of this type of failure were therefore investigated. The turbine speed was varied from 10,000 to 26,000 rpm and the blade temperature was varied, from $1500^{\circ}$ to $1900^{\circ}$ F. Twenty-one ceramal blades were investigated and compared with either Stellite 21 or S-816 alloy control blades.

Prior to the blade evaluation, the following physical property investigations were made: (a) the short-time tensile strengths of TiC plus Co plus (CbTaTi)C ceramal at $1800^{\circ}$ and $2200^{\circ}$ F to ascertain the strength of this material as compared with the 80 percent TiC plus 20 percent Co ceramal, (b) the modulus-of-rupture strengths of 65 percent TiC plus 20 percent Co plus 15 percent (CbTaTi)C and 65 percent TiC plus 20 percent Ni plus 15 percent (CbTaTi)C ceramals at $1800^{\circ}$, $2000^{\circ}$, $2200^{\circ}$ and $2400^{\circ}$ F to ascertain the effect upon strength of Ni and Co, and (c) the thermal-shock resistance of 80 percent TiC plus 20 percent Co, 65 percent TiC plus 20 percent Co plus 15 percent (CbTaTi)C, and 65 percent TiC plus 20 percent Ni plus 15 percent (CbTaTi)C ceramals. The physical test specimens and blades evaluated in this investigation were supplied by Kennametal, Inc.

This investigation was conducted at the NACA Lewis laboratory.

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## APPARATUS AND PROCEDURE

The apparatus and procedure used in this investigation are as follows:

### Experimental Materials

Composition and inspection. - The nominal chemical analyses as reported by the supplier are as follows:

| Composition | Ni (percent) | Co (percent) | TiC (percent) | (CbTaTi)C (percent) |
|---|---|---|---|---|
| I | | 20 | 80 | |
| II | | 20 | 65 | 15 |
| III | 20 | | 65 | 15 |

All experimental bodies were inspected for both internal and external flaws by radiographic and penetrant-oil methods, respectively. In addition, the blades were microscopically examined for surface cracks about the root.

Blade-root and mounting designs. - The following blade-root and mounting designs for the ceramal blades were used in this investigation:

(1) Conventional root (design A, fig. 1)

  (a) Copper plate 0.004, 0.008, and 0.080 inch thick and nickel plate 0.0025 and 0.080 inch thick; snug fit in wheel

  (b) No plate, loose fit in wheel

(2) Enlarged root (design B, fig. 1)

  (a) Platinum plate 0.005 or 0.0075 inch thick, snug fit in wheel

(3) Enlarged radii, copper inserts (design C, fig. 1), copper plate 0.005 inch thick; snug fit in wheel

(4) Alloy block cast around root (design D, fig. 1) snug fit in wheel

The roots were plated electrolytically. The lost-wax precision-investment casting technique was used to cast alloy blocks around the ceramal-blade roots in the case of design D.

Alloy control blades. - The blades used as standards for comparison (control blades) were fabricated of Stellite 21 or S-816 alloys (references 3 and 4); these alloys had the following nominal compositions:

| Alloy | C | Mn | Si | Cr | Ni | Mo | B | Fe | Co | P | S | W | Cb plus Ta |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stellite 21 | 0.20-.35 | 1.00 max | 1.00 max | 25.00-29.00 | 1.75-3.75 | 5.00-6.00 | 0.007 max | 2.00 max | bal. | | | | |
| S-816 | .32-.42 | 1.00-2.00 | 1.00 max | 19.00-21.00 | 19.00-21.00 | 3.50-4.50 | | 5.00 max | 40.0 min | 0.040 max | 0.030 max | 3.50-4.50 | 3.50-4.50 |

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These materials are currently being used for service-engine blades. The alloy blades were also radiographed to detect internal flaws and visually inspected for external flaws. The alloy and ceramal blades were similar as regards airfoil length and configuration.

## Evaluation of Physical Properties

Tensile strength. - Short-time tensile-strength evaluations of the TiC plus Co plus (CbTaTi)C ceramals at 1800° and 2200° F were conducted by use of the apparatus illustrated in figure 2. A ceramal specimen is illustrated in figure 3; the test-section diameter was 0.505 inch. A hydraulic tensile machine (0.50 percent maximum machine error) equipped with an automatic-temperature-controlled commercial silicon carbide tube furnace was used. The furnace was provided with a helium atmosphere. Specimen temperature was measured with a platinum - platinum-13-percent-rhodium thermocouple located at the center of the specimen gage length.

Bending stresses in the specimen were minimized by room-temperature alinement of the specimen and the linkage. Alinement measurements were made with electric wire strain gages mounted on the specimen at 90° radial positions at the center of the gage length and at nominal loads of 500 and 3000 pounds per square inch. Specimen alinement was considered satisfactory, when the bending stresses were less than 20 percent of the average tensile stress. After alinement, the specimens were raised to a temperature of 100° F above the test temperature and soaked for 4 hours at a nominal load of 500 pounds per square inch. At the completion of the soaking period, the temperature was reduced to the testing temperature. A nominal loading rate of 2000 pounds per square inch per minute was used.

Modulus-of-rupture evaluation. - The apparatus used in the modulus-of-rupture evaluations is pictured in figure 4. The specimen was loaded by filling the water receiver with water. When specimen failure occurred, the water supply was shut off. The specimens were 1/4 by 1/2 by 4 inches. Evaluations of the TiC plus Co plus (CbTaTi)C and the TiC plus Ni plus (CbTaTi)C ceramals were conducted at 1800°, 2000°, 2200° and 2400° F.

The specimens were supported by two silicon carbide knife edges spaced 3.5 inches apart and loaded at the center by means of a third opposing knife edge. Oxidation of the specimens during evaluation was minimized by placing the specimen and the knife edges in an argon-atmosphere chamber mounted within the furnace; argon was used at a flow rate of 40 cubic feet per minute. After the specimen was placed in the atmosphere chamber, 10 minutes was allowed for the specimen to heat to the evaluation temperature prior to loading. A nominal loading rate of 2000 pounds per square inch per minute in the extreme outer fiber at the specimen midpoint was used. The specimen temperature was measured by the use of a platinum - platinum-13-percent-rhodium thermocouple. The permanent set was converted to percentage elongation E by the use of the following equation:

$$E = \frac{2\sqrt{\left(\frac{L}{2}\right)^2 + (\delta)^2} - L}{L} \times 100$$

where

$L$ length between supporting knife edges, in.

$\delta$ permanent set, in.

Thermal-shock resistance. - Thermal-shock resistance of TiC plus Co and TiC plus Co plus (CbTaTi)C, and TiC plus Ni plus (CbTaTi)C ceramals was determined with the apparatus illustrated in figure 5. The specimen was transferred from the furnace to the quenching chamber by the use of a spring-loaded holder (reference 5). The test consisted in heating a disk specimen (2-in. diam. and 1/4 in. thick) for 10 minutes, then quenching it in an air stream at 70° to 80° F. Testing was carried out at 1800°, 2000°, 2200°, and 2400° F; at each temperature, the specimen was quenched 25 times for a cumulative total of 100 cycles or to failure, whichever occurred first. A quenching air velocity of approximately 265 feet per second (50 lb/min at 70° to 80° F) was used initially. The velocity was then increased to a value of 495 feet per second (127 lb/min at 70° to 80° F). A number of specimens were quenched from 2600° F, with the latter air velocity.

After the air-thermal-shock tests were completed, additional water-thermal-shock tests were made in an effort to differentiate between the thermal-shock resistance of the TiC plus (CbTaTi)C plus Co ceramal and the TiC plus (CbTaTi)C plus Ni ceramals. This test consisted in heating a disk in a conventional muffle furnace for 10 minutes then quenching it in agitated water at 40° to 50° F. Each specimen was quenched five cycles from 1800° F and five cycles from 2000° F or until failure, whichever occurred first. The disks used had been previously subjected to air-thermal-shock tests.

After each air- or water-quenching cycle, the specimens were examined visually for evidence of cracking. When cracking (failure) was not apparent but suspected, the specimens were radiographically inspected.

### Turbine-Blade Evaluation

Wheel modification. - The turbine wheel was altered in the following manner to accommodate ceramal-blade root designs B to D, inclusive: A number of existing dovetail slots in the wheel were completely filled with weld material and this segment was machined to the necessary shape. 2515
Adjacent blades were omitted to lessen the stress on this segment of the wheel. Blades not a part of the alloy control group were cut to about 3/4 their original length to prevent failure and at the same time to permit desired speeds to be reached. A typical wheel, prior to operation, is illustrated in figure 6. The wheels were dynamically balanced prior to operation and thereafter, as necessary. Balancing was generally accomplished by removal of material from nontest blades rather than from the wheel.

Phases of blade evaluation. - The evaluation of the blades can be divided into three phases; the first phase had the following two objectives:

(1) Evaluation of the following methods of minimizing the possibility of ceramal-blade root failure:

- (a) No root plate, loose fit in wheel
- (b) Copper root plate, 0.080 inch thick, snug fit in wheel
- (c) Nickel root plate, 0.0025 and 0.080 inch thick, snug fit in wheel
- (d) Alloy block cast around ceramal-blade root, design D (fig. 1), snug fit in wheel

(2) Observation of the effectiveness of (CbTaTi)C in inhibiting blade oxidation during operation.

All blades were of compositions I or II and were of design A (fig. 1) except as noted previously. Two speeds, 10,000 and 15,000 rpm, were used, and the estimated blade temperature was varied from 1500° to 1900° F.

The second phase of the evaluation was designed to examine the possibility of using the ceramals in a highly stressed blade application. The following four methods were concurrently studied as means of preventing ceramal-blade root failure:

(1) Copper root plate, 0.004 and 0.008 inch, snug fit in wheel

(2) Copper root shim, 0.005 inch, snug fit in wheel

(3) Platinum root plate, 0.005 and 0.0075 inch, snug fit in wheel

(4) Enlarged root radii (blade design C, fig. 1), copper plate 0.005 thick; snug fit in wheel

Blades of compositions II and III were used. Blade design B (fig. 1) was used except as noted previously. The turbine was run at a speed of 26,000 rpm, which resulted in a simple centrifugal stress of approximately 20,000 pounds per square inch at the midspan of
2515 the Stellite 21 alloy control blades and 14,000 pounds per square inch at the midspan of the ceramal blades (the density of the ceramal was 5.8 g/cc and the density of the alloy was 8.3 g/cc). The estimated blade temperature was 1600° F, about 100° F higher than current blade temperatures.

The third phase of the evaluation was designed to investigate the possibility of utilizing a ceramal for blades in moderately severe applications. In this phase, the turbine was run at a speed of 22,850 rpm, which resulted in a stress of 16,000 pounds per square inch at the midspan of the S-816 alloy control blades and a stress of 10,700 pounds per square inch at the midspan of the ceramal blades. (A Stellite 21 blade group was also used for purposes of comparison). The estimated blade temperatures were 1500° and 1700° F. A blade of composition III and of design B (fig. 1) was used; the blade had a platinum root plate of 0.0075 inch.

Turbine unit and operation. - The evaluation unit consisted of a turbojet combustion chamber and a small free-running gas turbine described in reference 1. The gas turbine is shown in figure 7. Blade temperature was indicated by the average of four nozzle-box thermocouple readings. The operation of the turbine is as follows.

The turbine was motored with air for 5 minutes to purge the piping system of accumulated gases. Combustion was begun and operating conditions were obtained in about 3 minutes. These conditions were maintained until blade failure occurred; shutdowns were made overnight. When blade failure occurred, which was indicated by a change in the pitch of the sound coming from the unit, combustion was immediately stopped and the wheel speed was quickly reduced to minimize effects of vibration. Operating time was measured from the beginning to end of combustion. The alloy control blades that failed were replaced by similar blades in order to preserve balance conditions. Damage to blades due to blade fragments was minimized by use of a fragment shield. This shield consisted of thin sheet metal backed by several thicknesses of asbestos sheet about the turbine (fig. 7).

## RESULTS AND DISCUSSION

### Evaluation of Physical Properties

The results of the evaluation of the physical properties are as follows:

Tensile strength. - The results of the elevated-temperature tensile-strength evaluations of the 65 percent TiC plus 20 percent Co plus 15 percent (CbTaTi)C ceramal are shown in table I. Figure 8 shows a comparison of the tensile strengths of this ceramal and the 80 percent TiC plus 20 percent Co ceramal of reference 6. The use of 15 percent of the mixed carbide solid solution of Ta, Cb, and Ti can be associated with a reduction in the average tensile strengths from 33,200 to 32,000 pounds per square inch and from 11,050 to 8000 pounds per square inch at 1800° and 2200° F, respectively. Modified TiC ceramal specimens containing nickel were not available and were not included in this particular evaluation. Elongation was not measured.

Modulus of rupture. - The modulus-of-rupture strengths of the TiC plus (CbTaTi)C ceramals containing 20 percent Co or 20 percent Ni are shown in table II. A comparison of the modulus-of-rupture strengths of these ceramals is presented in figure 9 wherein it is shown that the 20 percent nickel ceramal is lower in strength than the 20 percent cobalt ceramal at all temperatures studied. The average reductions in strength are from 57,700 to 47,900 pounds per square inch, from 36,300 to 24,650, from 17,900 to 9950, and from 1000 to 975 pounds per square inch for 1800°, 2000°, 2200°, and 2400° F, respectively. Apparently, the use of nickel rather than cobalt in the TiC plus (CbTaTi)C ceramal results in less strength. The calculated percent elongation for either material is negligible, as may be seen from table II.

Thermal shock. - The results of the thermal-shock evaluation of the three ceramal compositions are presented in table III. Both the TiC plus (CbTaTi)C ceramals containing either 20 percent cobalt or 20 percent nickel survived the 100 cycles of testing when quenched with air at 265 feet per second. The air velocity was therefore increased to 495 feet per second in an effort to cause specimen failure in order to differentiate among the thermal-shock resistance of these materials. In this test, three out of three 80 percent TiC plus 20 percent Co ceramal specimens survived 100 cycles. One specimen out of three of the 65 percent TiC plus 20 percent Co plus 15 percent (CbTaTi)C ceramal survived 100 cycles of testing; the remaining two specimens of this composition failed during the 50th and 52nd cycles. The specimens failing at the 52nd cycle was chipped inadvertedly during testing and failed as a result of this chip. Two TiC plus Ni plus (CbTaTi)C specimens survived 100 cycles; one specimen failed at 34 cycles. The temperature was then increased to 2600° F in an effort to further differentiate among the thermal-shock resistance of these three materials. One specimen of the TiC plus Co plus (CbTaTi)C ceramal which had successfully survived 100 cycles of testing with air at 495 feet per second was subjected to an additional 22 cycles at 2600° F for a total of 122 cycles before failure; some oxidation occurred. One specimen of the 80 percent TiC plus 20 percent Co ceramal which had been tested previously with air at a velocity of 495 feet per second was then tested at 2600° F. This specimen failed after 5 cycles at 2600° F for a total of 105 cycles. However, this specimen suffered severe oxidation at this temperature, and the results of this particular test could not be properly interpreted; hence, further testing at this condition was discontinued.

In order to differentiate between the thermal-shock resistance of the TiC plus (CbTaTi)C plus either Ni or Co, the water-thermal-shock test was used. The water-quench test was comparatively free of oxidation effects. Specimens previously quenched at the lower air velocity were used. The results presented in table III suggest that the ceramal containing cobalt has the better thermal-shock resistance. The relative thermal-shock resistance of the three compositions considered, in order of decreasing superiority, would appear to be (a) 80 percent TiC plus 20 percent Co, (b) 65 percent TiC plus 20 percent Co plus 15 percent (CbTaTi)C and (c) 65 percent TiC plus 20 percent Ni plus 15 percent (CbTaTi)C.

During the air-thermal-shock test, the oxidation resistance of the ceramals containing (CbTaTi)C was observed to be superior to that of the 20 percent Co plus 80 percent TiC ceramal. It has been found that the oxidation resistance of a TiC ceramal containing approximately 20 percent Ni is somewhat poorer in oxidation resistance than that of an 80 percent TiC plus 20 percent Co ceramal. Hence, the use of (CbTaTi)C with either TiC plus Co or TiC plus Ni ceramals probably results in improved oxidation resistance.

## Turbine-Blade Evaluation

Phase 1, low-stress operation. - The first phase of the blade evaluation revealed that the use of (CbTaTi)C in the TiC plus Co ceramal greatly inhibits blade oxidation during operation; this is in agreement with the data reported in reference 2. From tables IV and V (runs 1 to 3, inclusive), it is seen that: (a) Better results were obtained with plated, snug-fitted roots than with nonplated, loose-fitted roots, (b) copper plate was more effective than nickel plate in preventing ceramal-blade-root failure, (c) the alloy block cast about the ceramal-blade root was somewhat effective in preventing root failure but probably not so effective as the copper plate, and (d) blade design A (fig. 1) was inadequate for the low-stress high-temperature operation.

The loosely fitted blades were investigated on the premise that the major cause of root failure is vibratory stress and that these stresses could be lessened, if the blade were permitted to pivot in the dovetail slot rather than be rigidly held. The results indicate, however, that high local stresses caused by surface imperfections or poor fit of the blade in the wheel, or both, are more likely to cause blade failure, 2515
and that a blanket of a ductile material between the blade and wheel redistributes high local stresses.

Root design D, illustrated in figure 1, was investigated on the assumption that an alloy block cast about a ceramal blade root would fuse to the blade, and an intimate contact, which would be maintained, would result. A metallographic study of the alloy-ceramal interface (fig. 10) revealed that the ceramal and S-816 alloy block did not fuse. This presented the possibility that either plastic deformation or differential expansion would occur, upset the contact, and result in high local stresses. A failed blade (25.3 hr of operation) of this design is shown in figure 11. Because the coefficient of expansion of the S-816 alloy used is about 60 percent greater than that of the ceramal material, it is likely that thermal stresses were introduced into the root and hastened the failure of these blades.

Two blades, used in run 2, were run 78 and 111 hours at temperatures of $1500^{\circ}$ to $1900^{\circ}$ F and at speeds of 10,000 to 15,000 rpm. After 78 hours 94 percent and after 111 hours 95 percent of the 136 Stellite 21 blades had failed. These ceramal blades experienced negligible oxidation.

Phase 2, severe-stress operation. - The results of this phase of the evaluation may be obtained from a study of runs 4 to 9 inclusive, tables IV and V. With the exception of one blade which was destroyed as a result of a wheel-rim failure, all ceramal blades failed at the neck-roll junction. The results are not conclusive regarding optimum root-plate thickness. Platinum is the most desirable material inasmuch as it deteriorated less. The two blade designs, B and C, and the various root plates investigated were not satisfactory for this severe-stress operation. Platinum plate over 0.008 inch thick was impracticable to obtain, and because the object was to compare copper and platinum on an equal-thickness basis, the copper plate was limited to 0.008 inch. The blade of design C, TiC plus Ni plus (CbTaTi)C, ran for 2.8 hours; failure occurred in the root above the neck-roll junction as illustrated in figure 12. It is thus indicated that this arrangement did relieve stress-concentration at the neck-roll junction but caused another part of the root to become critical. Further investigation of this approach is apparently indicated. The use of 0.005-inch-thick copper shim was investigated as a convenient and expeditious method; this method was found not to be very promising.

Phase 3, moderate-stress operation. - The results of this phase of the investigation are presented in tables IV and V (run 10). The TiC plus Ni plus (CbTaTi)C ceramal blade performed very well; it outlasted a 10-blade Stellite 21 alloy sample and a 3-blade S-816 alloy sample. At the end of 124 hours of operation, 99 hours were at 1500° F and 25 hours were at 1700° F, the ceramal blade was still intact, although nicked and gouged (fig. 13). During this time of operation, the ceramal blade was only slightly oxidized.



## CONCLUDING REMARKS

The results indicate that both the 65 percent TiC plus 20 percent Co plus 15 percent (CbTaTi)C and 65 percent TiC plus 20 percent Ni plus 15 percent (CbTaTi)C ceramals should certainly be considered further for gas-turbine-blade use. The oxidation resistance of either of these materials appears to be adequate for practical blade application.

Further work is required on the blade root design and mounting method.

## SUMMARY OF RESULTS

An investigation of the turbine blade life and of some of the physical properties of titanium carbide base ceramals containing either nickel or cobalt and with or without the addition of a solid solution of the mixed carbides of columbium, titanium, and tantalum yielded the following results.

1. Two TiC plus Co plus (CbTaTi)C blades ran 78 and 111 hours and survived 94 and 95 percent, respectively, of a 136-blade Stellite 21 alloy sample at temperatures of 1500° and 1900° F. The wheel speed was 10,000 to 15,000 rpm. A third blade, TiC plus Ni plus (CbTaTi)C ran 99 hours at 1500° F and 25 hours at 1700° F without failure; during this time, 100 percent each of a 10-blade Stellite 21 alloy sample and of a 3-blade S-816 alloy sample failed. The remaining 18 ceramal blades investigated yielded poor results, compared with their respective alloy control blades.

2. The use of platinum, copper, or nickel plate on the base of the ceramal blades was effective in extending blade root life; platinum appeared most effective.

3. The average short-time tensile strengths of the 80 percent TiC plus 20 percent Co ceramal at 1800° and 2200° F were 33,200 and 11,050 pounds per square inch, respectively, while the short-time tensile

strengths for a 65 percent TiC plus 20 percent Co plus 15 percent (CbTaTi)C ceramal were 32,000 and 8000 pounds per square inch, respectively. The use of nickel rather than cobalt in the TiC plus (CbTaTi)C ceramal reduced the average modulus-of-rupture strengths at 1800°, 2000°, 2200°, and 2400° F from 57,700 to 47,900 pounds per square inch, from 36,300 to 24,650 pounds per square inch, from 17,900 to 9950 pounds per square inch, and from 1000 to 975 pounds per square inch, respectively. The thermal-shock resistance of the TiC plus Co ceramal was better than that of the TiC plus Co plus (CbTaTi)C ceramal, which in turn was better than that of the TiC plus Ni plus (CbTaTi)C ceramal.

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4. The use of a solid solution of the mixed carbides of Ta, Ti, and Cb in the TiC plus Co and TiC plus Ni ceramals inhibited oxidation during operation.

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TABLE I - TENSILE STRENGTH OF 65 PERCENT TiC PLUS 20 PERCENT Co PLUS 15 PERCENT (CbTaTi)C CERAMAL

[Loading rate, 2000 lb/min]

| Specimen | Soak | | Tensile strength (lb/sq in.) at | |
|---|---|---|---|---|
| | Time (hr) | Temperature ($^{\circ}$F) | 1800$^{\circ}$ F | 2000$^{\circ}$ F |
| 1 | 4 | 1900 | 30,100 | |
| 2 | 4 | 1900 | 32,000 | |
| 3 | 4 | 1900 | 33,800 | |
| 4 | 4 | 2300 | | 7800 |
| 5 | 4 | 2300 | | 8200 |

TABLE II - MODULUS OF RUPTURE OF MODIFIED TiC BASE CERAMALS TESTED ON 3.5-INCH SPAN AND LOADED AT 2000 POUNDS PER SQUARE INCH PER MINUTE 2515

| Specimen | Measured density (g/cu cm) | Modulus of rupture (lb/sq in.) at | | | | Permanent set (in.) | Calculated plastic elongation (percent) |
|---|---|---|---|---|---|---|---|
| | | 1800° F | 2000° F | 2200° F | 2400° F | | |
| 65 percent TiC plus 20 percent Co plus 15 percent (CbTaTi)C | | | | | | | |
| 6 | | 59,200 | | | | 0.020 | 0.009 |
| 7 | 5.99 | 55,800 | | | | .020 | .007 |
| 8 | 6.00 | 58,150 | | | | .019 | .006 |
| 9 | 6.13 | | 35,850 | | | .040 | .026 |
| 10 | | | 35,400 | | | .030 | .015 |
| 11 | | | 37,700 | | | .043 | .030 |
| 12 | | | | 18,750 | | .055 | .049 |
| 13 | | | | 17,700 | | .067 | .073 |
| 14 | | | | 17,300 | | .070 | .080 |
| 15 | | | | | 1050 | .016 | .004 |
| 16 | | | | | 1000 | .004 | .001 |
| 17 | | | | | 1000 | .005 | .001 |
| 65 percent TiC plus 20 percent Ni plus 15 percent (CbTaTi)C | | | | | | | |
| 18 | 5.77 | 46,350 | | | | 0.016 | 0.004 |
| 19 | 5.75 | 47,700 | | | | .016 | .004 |
| 20 | | 49,700 | | | | .024 | .010 |
| 21 | | | 24,200 | | | .018 | .005 |
| 22 | | | 24,200 | | | .015 | .004 |
| 23 | | | 25,500 | | | .019 | .006 |
| 24 | | | | 9,150 | | .026 | .011 |
| 25 | | | | 10,100 | | .024 | .010 |
| 26 | | | | 10,600 | | .023 | .009 |
| 27 | | | | | 1000 | .028 | .013 |
| 28 | | | | | 950 | .015 | .004 |

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TABLE III - THERMAL-SHOCK RESULTS ON TiC AND MODIFIED

TiC BASE CERAMALS

| Specimen | Air quench; Number of cycles completed; Quenched from °F by air at velocity of 495 ft/sec (a) | | | | Total number of cycles | Water quench; Number of cycles completed; Quenched from °F into 40° to 45° F water | |
|---|---|---|---|---|---|---|---|
| | 1800° F | 2000° F | 2200° F | 2400° F | | 1800° F | 2000° F |
| 65 percent TiC plus 20 percent Co plus 15 percent (CbTaTi)C | | | | | | | |
| [b]29 | 25 | 25 | 25 | 25 | 100 | 5 | 1 |
| [b]30 | 25 | 25 | 25 | 25 | 100 | 5 | - |
| [c]31 | 25 | 25 | 2 | -- | 52 | - | - |
| 32 | 25 | 25 | -- | -- | 50 | - | - |
| [d]33 | 25 | 25 | 25 | 25 | 100 | - | - |
| 80 percent TiC plus 20 percent Co | | | | | | | |
| [e]34 | 25 | 25 | 25 | 25 | 100 | - | - |
| 35 | 25 | 25 | 25 | 25 | 100 | - | - |
| 36 | 25 | 25 | 25 | 25 | 100 | - | - |
| 65 percent TiC plus 20 percent Ni plus 15 percent (CbTaTi)C | | | | | | | |
| [b]37 | 25 | 25 | 25 | 25 | 100 | 1 | - |
| 38 | 25 | 9 | -- | -- | 34 | - | - |
| 39 | 25 | 25 | 25 | 25 | 100 | - | - |
| 40 | 25 | 25 | 25 | 25 | 100 | - | - |

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[a]Except where noted.

[b]Quenched with air at velocity of 265 ft/sec.

[c]This specimen was blown out of holder and chipped; crack originated from chip.

[d]Twenty-two additional cycles at 2600° F.

[e]Five additional cycles at 2600° F; heavily oxidized.

TABLE IV - SUMMARY OF TURBINE-BLADE EVALUATION

| Operational data | | | | Ceramal blade data | | | | Alloy blade data | |
|---|---|---|---|---|---|---|---|---|---|
| Run | Maximum speed (rpm) | Maximum blade temperature (°F) | Total time (hr) | Root design (a) | Mounting | Number of ceramal blades | Composition of ceramal (b) | Number of alloy blades (c) | Alloy blades failed at failure of last ceramal blade (percent) |
| | | | | Phase 1 | | | | | |
| 1 | 12,500 | 1900 | 4.72 | A | Nickel, 0.0025 in. | 6 | II | 136 | 25 |
| 2 | 15,000 | 1900 | 111.0 | A | No plate, loose fit<br>Cu plate, 0.080 in. snug fit<br>Ni plate, 0.080 in. snug fit | 2<br>2<br>2 | II | 136 | 95 |
| 3 | 15,000 | 1900 | 25.3 | D | | 2 | I, II | 21 | 57 |
| | | | | Phase 2 | | | | | |
| 4 | 26,000 | 1600 | 5.26 | B | Cu plate, 0.004 in. | 1 | II | 20 | 0 |
| 5 | 26,000 | 1600 | 2.90 | B | Cu plate, 0.008 in. | 1 | II | 20 | 0 |
| 6 | 26,000 | 1600 | 19.25 | B | Pt plate, 0.0075 in. | 1 | II | 20 | 60 |
| 7 | 22,500 | 1600 | 5.26 | B | Pt plate, 0.005 in. | 1 | II | 20 | 0 |
| 8 | 19,500 | 1600 | 1.12 | B | Cu shim, 0.005 in. | 1 | III | 20 | 0 |
| 9 | 26,000 | 1600 | 2.85 | C | Cu plate, 0.005 in., plus inserts at neck-roll junction radii | 1 | III | 20 | 0 |
| | | | | Phase 3 | | | | | |
| 10 | 22,850 | 1700 | 124.72 | B | Pt plate, 0.0075 in. | 1 | III | 10 Stellite 21<br>3 S-816 | 100<br>100<br>(d) |

[a]See fig. 1 for various root designs.
[b]See page 2 for corresponding compositions.
[c]Alloy blades of Stellite 21 alloy unless otherwise indicated
[d]Ceramal blade still intact after failure of all alloy blades.

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TABLE V - TABULATION OF TURBINE-BLADE OPERATION DATA

[Time to individual alloy-blade failures has been omitted.]

| Time (hr) | Cumulative time (hr) | Estimated blade temperature (°F) | Wheel speed (rpm) | Alloy samples failed (percent) | Ceramal samples failed (percent) | Remarks |
|---|---|---|---|---|---|---|
| Run 1: Number of alloy control blades, 136; number of ceramal blades, 6; ceramal blade, design A, modified TiC plus Co; ceramal-blade root plate, 0.0025-inch nickel. | | | | | | |
| 0.95 | 0.95 | 1500 | 10,000 | 0 | 0 | |
| .50 | 1.45 | 1600 | 10,000 | 0 | 0 | |
| .50 | 1.95 | 1700 | 10,000 | 0 | 0 | |
| .50 | 2.45 | 1800 | 10,000 | 0 | 0 | |
| .50 | 2.95 | 1850 | 10,000 | 0 | 0 | |
| .50 | 3.45 | 1900 | 10,000 | 0 | 17 | Ceramal failed at neck-roll junction. |
| 1.17 | 4.72 | 1900 | 12,500 | 25 | 100 | Ceramals failed at neck-roll junction. Vibration due to large number of blade failures may have induced additional failures. |
| Run 2: Number of alloy control blades, 136; number of ceramal blades, 6; ceramal blade, design A; modified TiC plus Co; ceramal-blade root plate: (1) 2 No plate, loose fit (2) 2 0.080-inch Ni plate, snug fit (3) 2 0.080-inch Cu plate, snug fit | | | | | | |
| 0.77 | 0.77 | 1500 | 10,000 | 0 | 0 | |
| .50 | 1.27 | 1600 | 10,000 | 0 | 0 | |
| .50 | 1.77 | 1700 | 10,000 | 0 | 0 | |
| .50 | 2.27 | 1800 | 10,000 | 0 | 17 | Type (1), ceramal blade failed. |
| .65 | 2.92 | 1850 | 10,000 | 0 | 17 | |
| .50 | 3.42 | 1900 | 10,000 | 0 | 17 | |
| 2.00 | 5.42 | 1900 | 12,500 | 0 | 33 | Type (1), ceramal blade failed. |
| .51 | 5.93 | 1900 | 15,000 | 0 | 50 | Type (2), ceramal blade failed. |
| 10.49 | 16.42 | 1900 | 15,000 | 6 | 67 | Type (2), ceramal blade failed. |
| 61.76 | 78.18 | 1900 | 15,000 | 94 | 84 | Type (3), ceramal blade failed. |
| 32.82 | 111.00 | 1900 | 15,000 | 95 | 100 | Type (3), ceramal blade failed. |
| Run 3: Number of alloy control blades, 21; number of ceramal blades, 2; ceramal blade, design D, plain and modified TiC plus Co blades. | | | | | | |
| 0.10 | 0.10 | 1900 | 15,000 | 0 | 50 | Ceramal failed at top of root casting. |
| 25.20 | 25.30 | 1900 | 15,000 | 57 | 100 | Ceramal failed at top of root casting |

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TABLE V - Continued. TABULATION OF TURBINE-BLADE OPERATION DATA

[Time to individual alloy-blade failures has been omitted.]

| Time (hr) | Cumulative time (hr) | Estimated blade temperature (°F) | Wheel speed (rpm) | Alloy samples failed (percent) | Ceramal samples failed (percent) | Remarks |
|---|---|---|---|---|---|---|
| Run 4: | Number of alloy control blades, 20; number of ceramal blades, 1; ceramal blade, design B, modified TiC plus Co; ceramal-blade root plate, 0.004-inch copper. | | | | | |
| 0.33 | 0.33 | 1600 | 15,000 | 0 | | |
| .17 | .50 | 1600 | 16,750 | 0 | | |
| .17 | .67 | 1600 | 18,000 | 0 | | |
| .17 | .84 | 1600 | 19,500 | 0 | | |
| .17 | 1.01 | 1600 | 20,750 | 0 | | |
| .17 | 1.18 | 1600 | 21,750 | 0 | | |
| .17 | 1.35 | 1600 | 23,000 | 0 | | |
| .17 | 1.52 | 1600 | 24,000 | 0 | | |
| .17 | 1.79 | 1600 | 25,000 | 0 | | |
| 3.47 | 5.26 | 1600 | 26,000 | 0 | 100 | Wheel dovetail slot failed, allowing ceramal blade to pull out and become destroyed |
| Run 5: | Number of alloy control blades, 20; number of ceramal blades, 1; ceramal blade, design B, modified TiC plus Co; ceramal-blade root plate, 0.008-inch copper. | | | | | |
| 0.25 | 0.25 | 1600 | 15,000 | 0 | | |
| .17 | .42 | 1600 | 16,750 | 0 | | |
| .17 | .59 | 1600 | 18,000 | 0 | | |
| .17 | .76 | 1600 | 19,500 | 0 | | |
| .17 | .93 | 1600 | 20,750 | 0 | | |
| .17 | 1.10 | 1600 | 21,750 | 0 | | |
| .17 | 1.27 | 1600 | 23,000 | 0 | | |
| .17 | 1.44 | 1600 | 24,000 | 0 | | |
| .17 | 1.61 | 1600 | 25,000 | 0 | | |
| 1.29 | 2.90 | 1600 | 26,000 | 0 | 100 | Ceramal failed at neck-roll junction |

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TABLE V - Continued. TABULATION OF TURBINE-BLADE OPERATION DATA

[Time to individual alloy-blade failures has been omitted.]

| Time (hr) | Cumulative time (hr) | Estimated blade temperature (°F) | Wheel speed (rpm) | Alloy samples failed (percent) | Ceramal samples failed (percent) | Remarks |
|---|---|---|---|---|---|---|
| Run 6: Number of alloy control blades, 20; number of ceramal blades, 1; ceramal blade design B, modified TiC plus Co; ceramal-blade root plate, 0.0075-inch platinum | | | | | | |
| 0.42 | 0.42 | 1600 | 15,000 | 0 | 0 | |
| .17 | .59 | 1600 | 16,750 | 0 | 0 | |
| .17 | .76 | 1600 | 18,000 | 0 | 0 | |
| .17 | .93 | 1600 | 19,500 | 0 | 0 | |
| .17 | 1.10 | 1600 | 20,750 | 0 | 0 | |
| .17 | 1.27 | 1600 | 21,750 | 0 | 0 | |
| .17 | 1.44 | 1600 | 23,000 | 0 | 0 | |
| .17 | 1.61 | 1600 | 24,000 | 0 | 0 | |
| .17 | 1.78 | 1600 | 25,000 | 0 | 0 | |
| 17.47 | 19.25 | 1600 | 26,000 | 60 | 100 | Ceramal blade failed at neck-root junction. |
| Run 7: Number of alloy control blades, 20; number of ceramal blades, 1; ceramal blade, design B, modified TiC plus Co; ceramal-blade root plate, 0.005-inch platinum. | | | | | | |
| 0.25 | 0.25 | 1600 | 15,000 | 0 | 0 | |
| .17 | .42 | 1600 | 16,750 | 0 | 0 | |
| .17 | .59 | 1600 | 18,000 | 0 | 0 | |
| .17 | .76 | 1600 | 19,500 | 0 | 0 | |
| .17 | .93 | 1600 | 20,750 | 0 | 0 | |
| .17 | 1.10 | 1600 | 21,750 | 0 | 0 | |
| 4.16 | 5.26 | 1600 | 22,500 | 0 | 100 | Ceramal blade failed at neck-roll junction. |
| Run 8: Number of alloy control blades, 20; number of ceramal blades, 1; ceramal blade, design B, modified TiC plus Ni; ceramal-blade root covered with 0.005-inch copper shim. | | | | | | |
| 0.53 | 0.53 | 1600 | 15,000 | 0 | 0 | |
| .17 | .70 | 1600 | 16,750 | 0 | 0 | |
| .17 | .87 | 1600 | 18,000 | 0 | 0 | |
| .25 | 1.12 | 1600 | 19,500 | 0 | 100 | Ceramal blade failed at neck-roll junction. |

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TABLE V - Concluded. TABULATION OF TURBINE-BLADE OPERATION DATA

[Time to individual alloy-blade failures has been omitted.]

| Time (hr) | Cumula-tive time (hr) | Estimated blade temper-ature ($^{\circ}F$) | Wheel speed (rpm) | Alloy samples failed (per-cent) | Ceramal samples failed (per-cent) | Remarks |
|---|---|---|---|---|---|---|
| Run 9: Number of alloy control blades, 20; number of ceramal blades, 1; ceramal blade, design C, modified TiC plus Ni; ceramal-blade root plate, 0.005-inch copper. | | | | | | |
| 0.33 | 0.33 | 1600 | 15,000 | 0 | 0 | |
| .17 | .50 | 1600 | 16,750 | 0 | 0 | |
| .33 | .83 | 1600 | 18,000 | 0 | 0 | |
| .25 | 1.08 | 1600 | 19,500 | 0 | 0 | |
| .17 | 1.25 | 1600 | 20,750 | 0 | 0 | |
| .17 | 1.42 | 1600 | 21,750 | 0 | 0 | |
| .17 | 1.59 | 1600 | 23,000 | 0 | 0 | |
| .17 | 1.76 | 1600 | 24,000 | 0 | 0 | |
| .17 | 1.93 | 1600 | 25,000 | 0 | 0 | |
| .92 | 2.85 | 1600 | 26,000 | 0 | 100 | Ceramal blade failed in neck-roll junction |

Run 10: Number of alloy control blades, 20 Stellite 21 and 3 S-816; number of ceramal blades, 1; ceramal blade, design B, modified TiC plus Ni; ceramal-blade root plate, 0.0075-inch platinum.

| Time (hr) | Cumula-tive time (hr) | Estimated blade temper-ature ($^{\circ}F$) | Wheel speed (rpm) | Alloy samples failed (percent) | | Ceramal sample failed (per-cent) | Remarks |
|---|---|---|---|---|---|---|---|
| | | | | Stellite 21 | S-816 | | |
| 99.18 | 99.18 | 1500 | 22,850 | 20 | 0 | 0 | |
| 25.54 | 124.72 | 1700 | 22,850 | 100 | 100 | 0 | Ceramal blade intact after operation |

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[redacted]

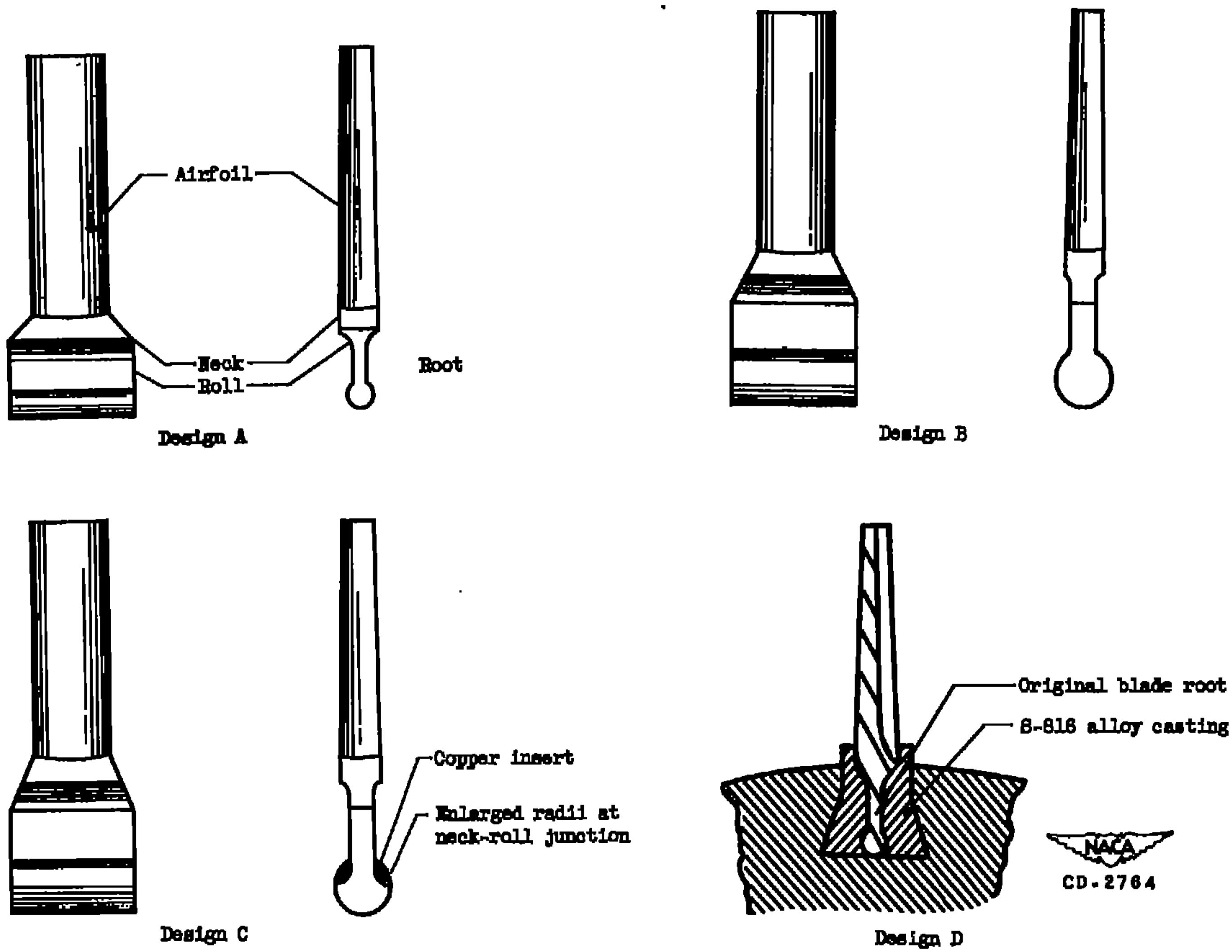


Figure 1. - Types of blade design used in investigation.

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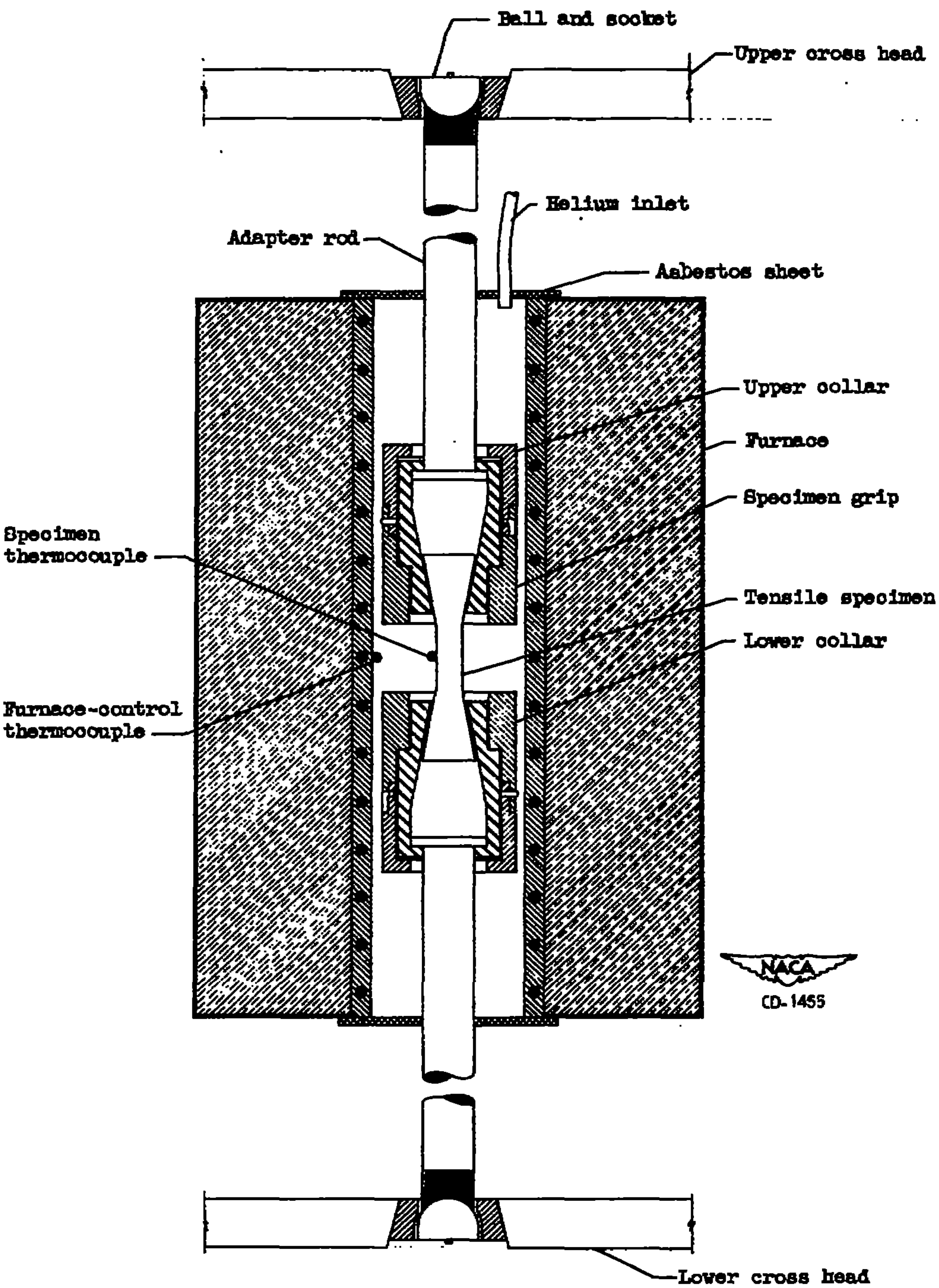


Figure 2. - Tensile-strength evaluation unit.

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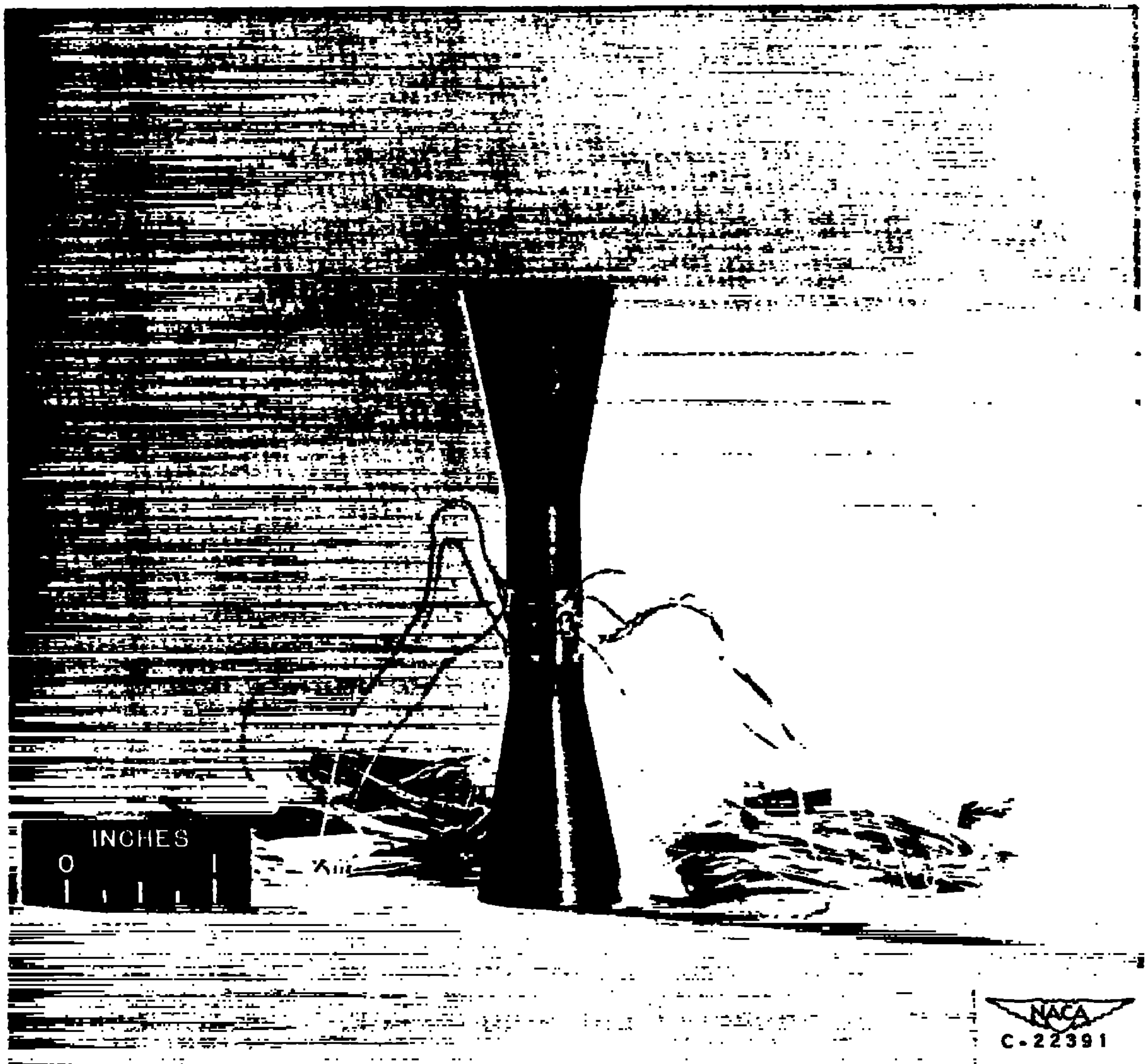


Figure 3. - Ceramal tensile-test specimen showing installation of strain gages.

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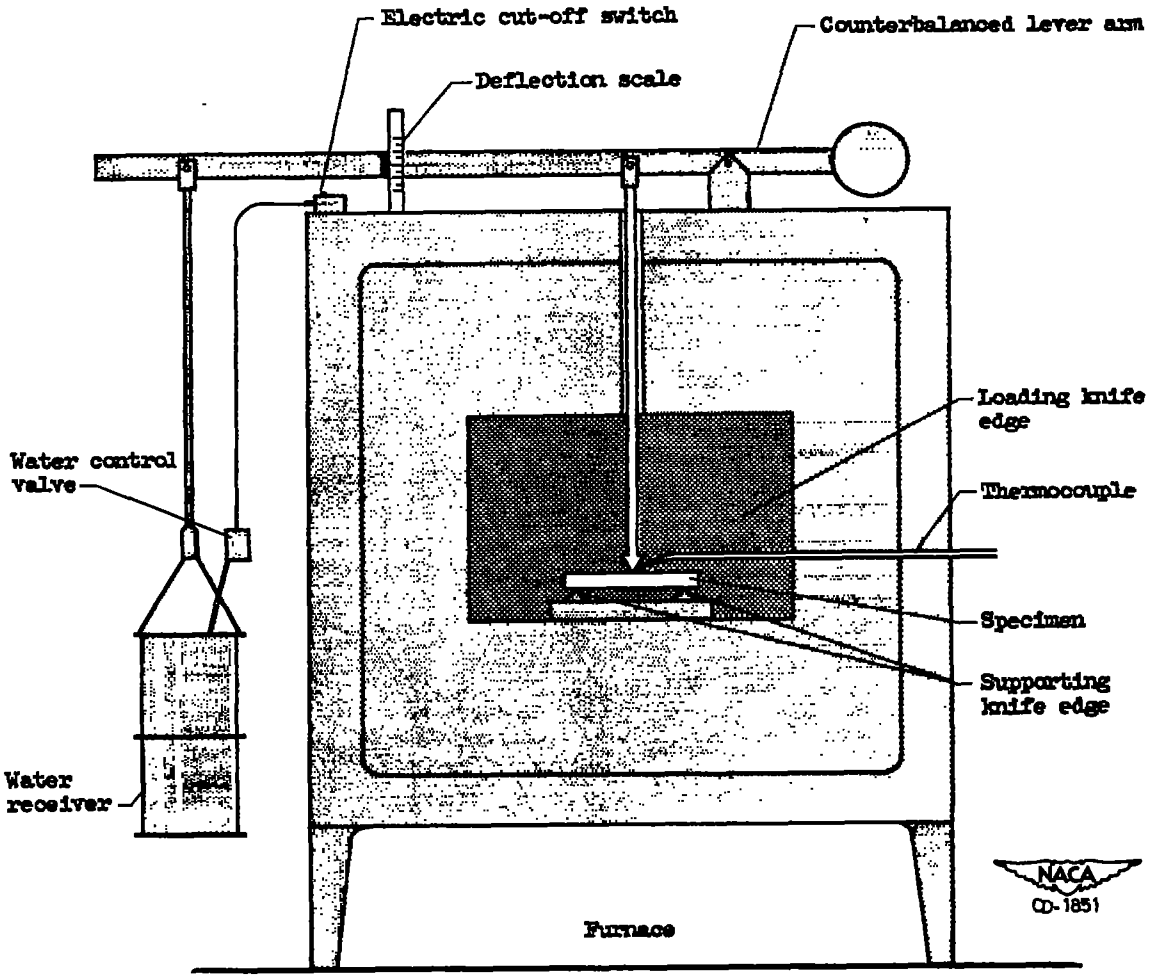


Figure 4. - Modulus-of-rupture evaluation apparatus.

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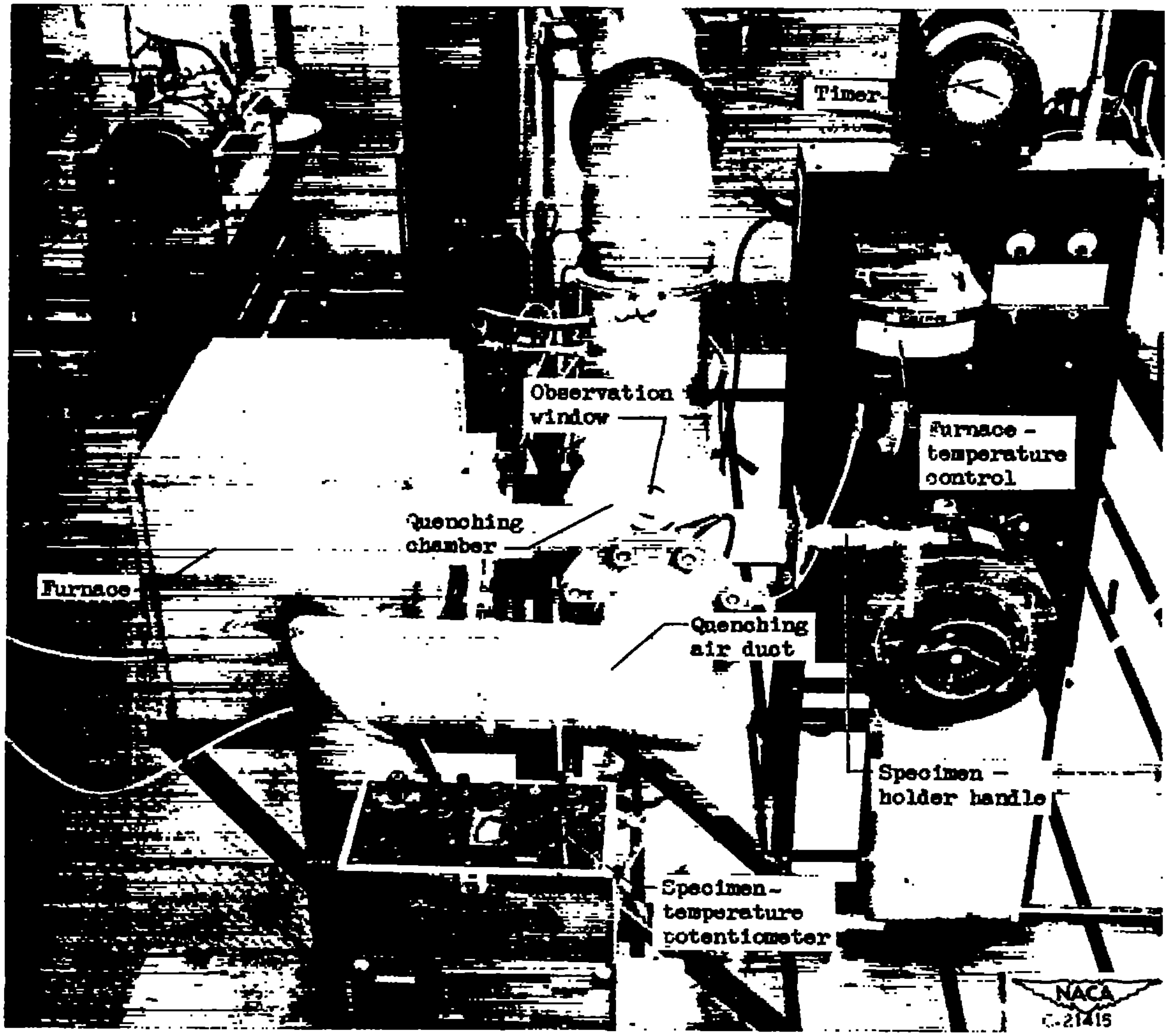


Figure 5. - Thermal-shock evaluation apparatus.

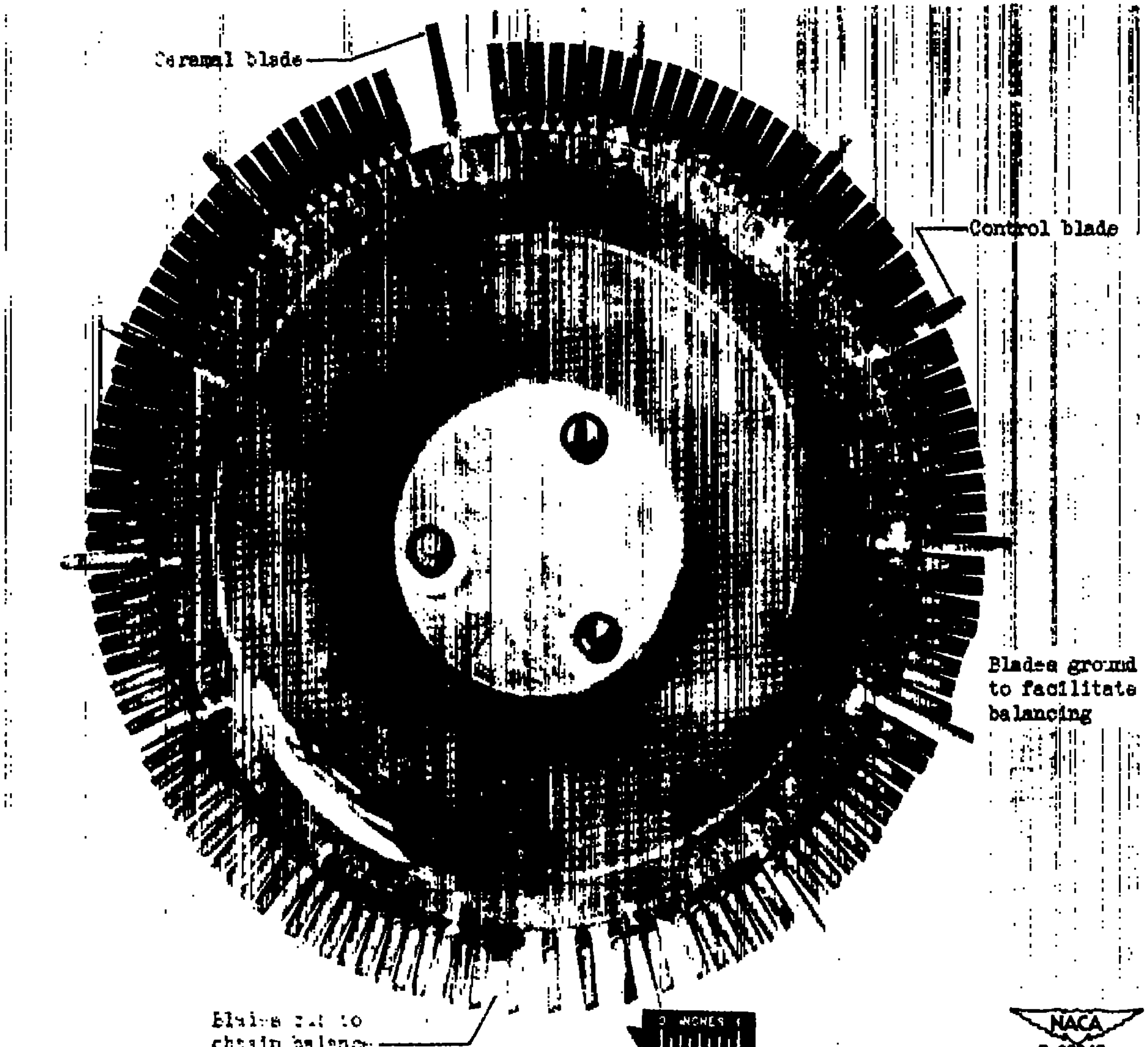


**Figure 6. - Installation of enlarged-root ceramal blade and arrangement of control blades in turbine wheel.**

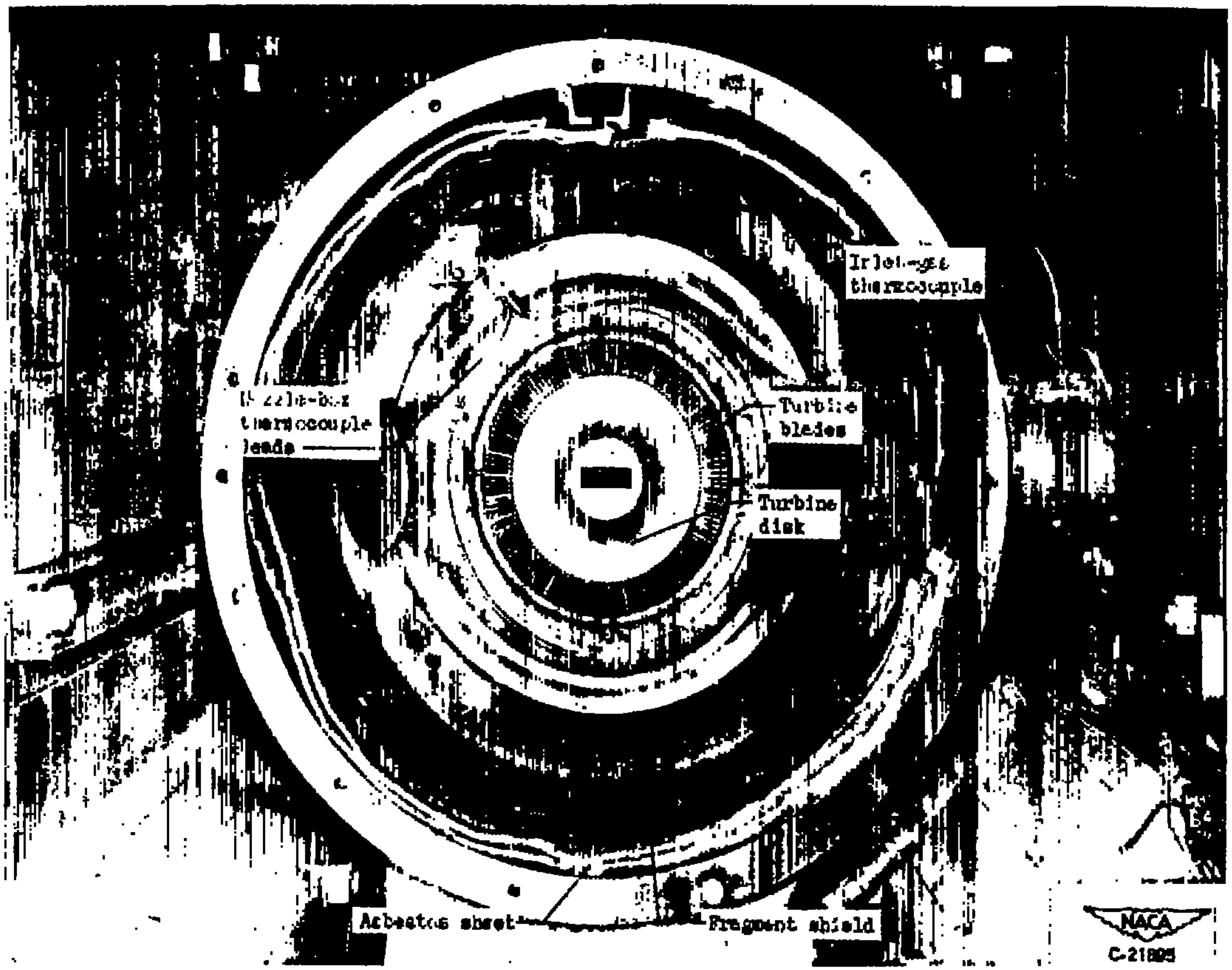


Figure 7. - Turbine-blade evaluation unit.

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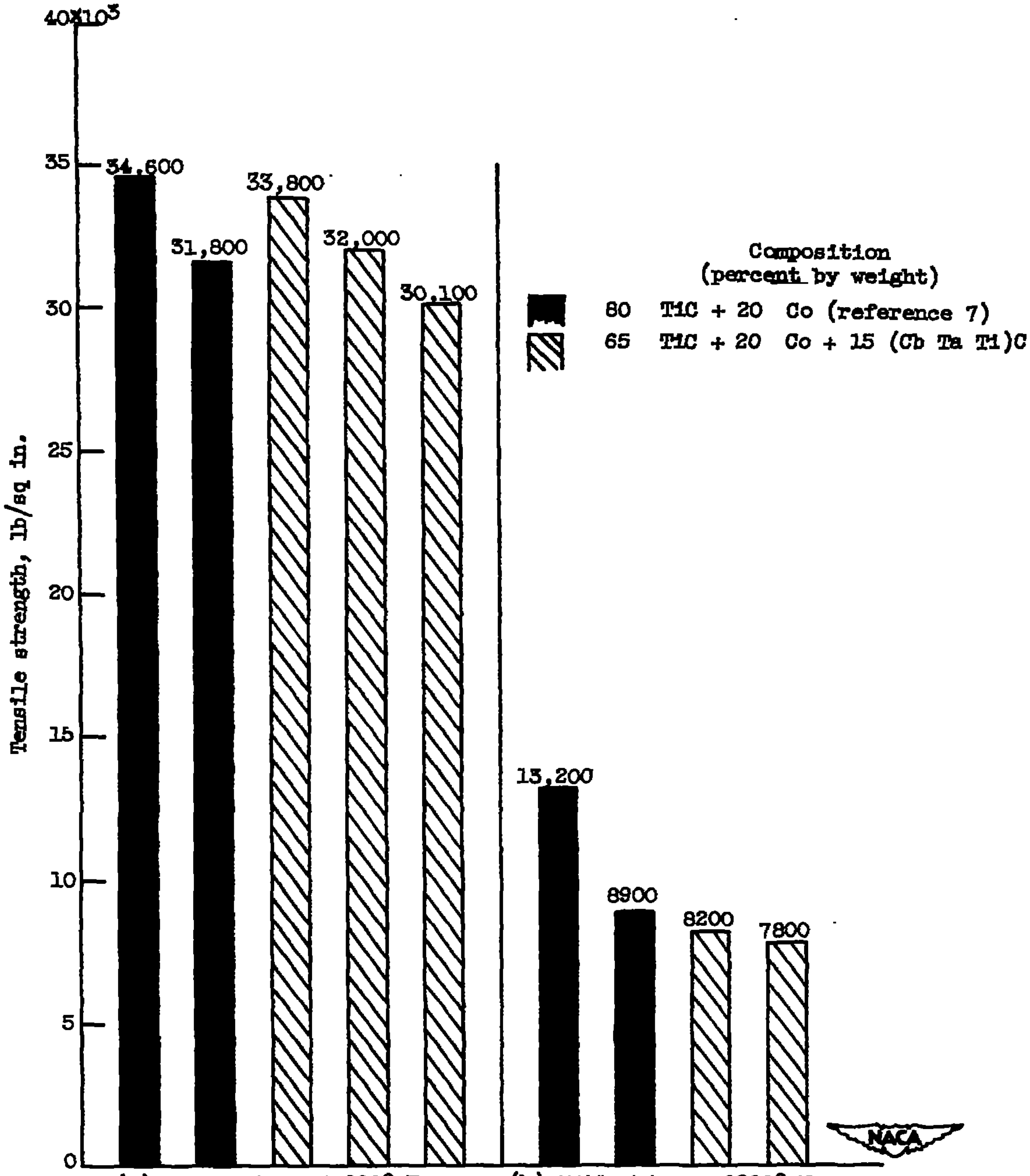


Figure 8. - Effect of modifying TiC plus Co ceramal by addition of 15 percent by weight of (Cb Ta Ti)C solid solution on short-time tensile strength.

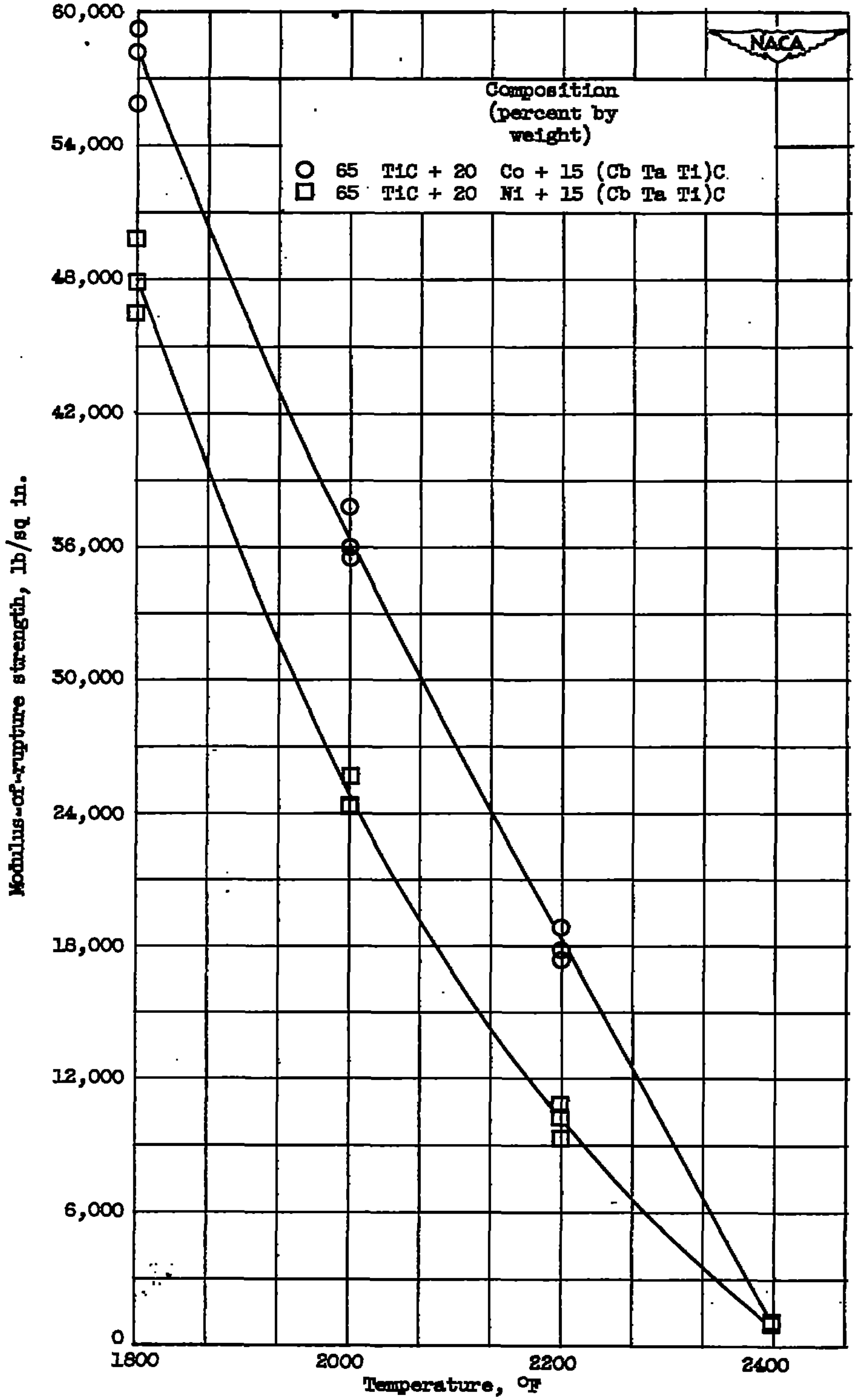


Figure 9. - Modulus-of-rupture strengths of modified TiC base ceramals.

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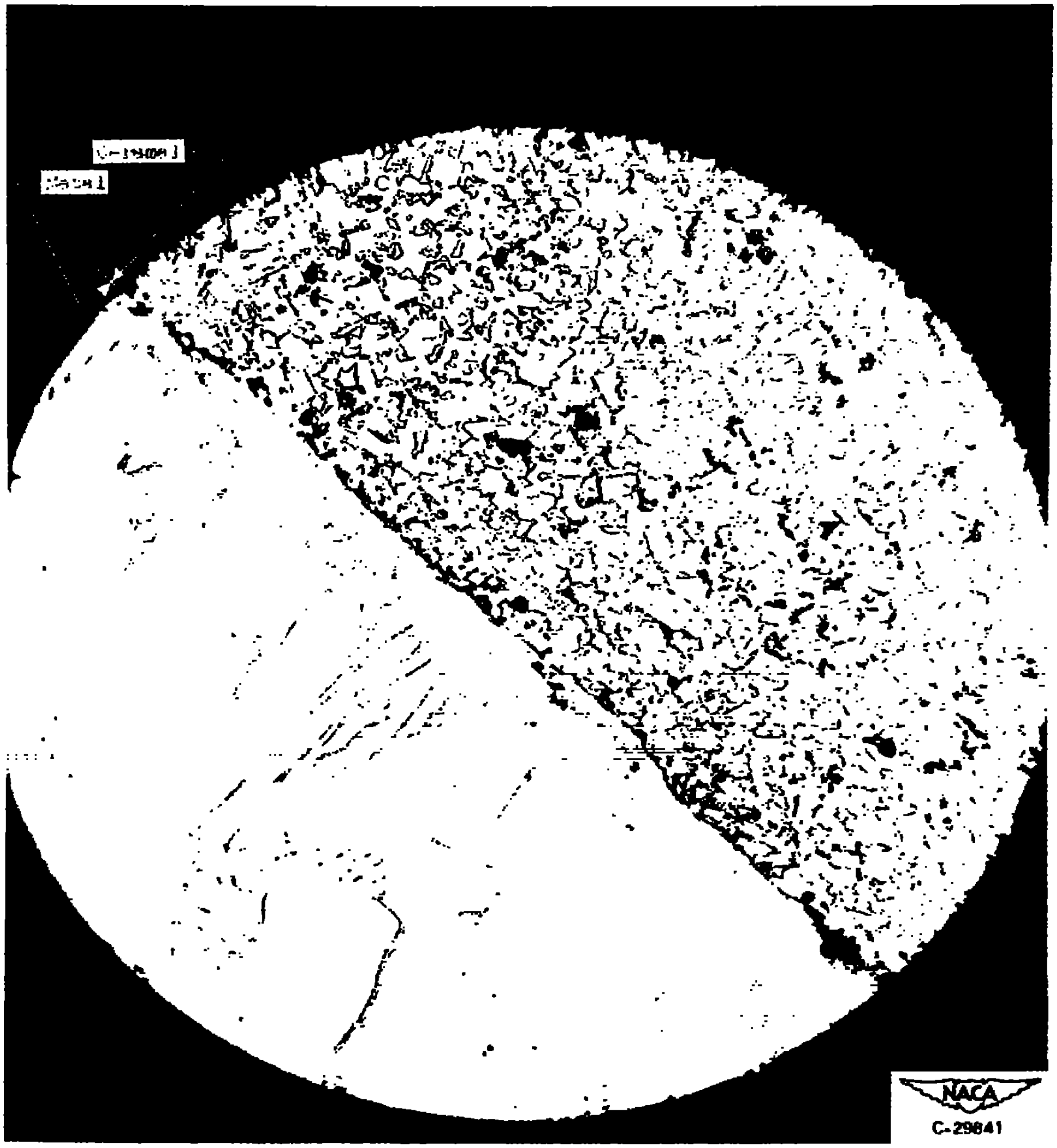


Figure 10. - TiC plus Co plus (Cb Ta Ti)C ceramal and S-816 interface. X500; unetched.

[redacted]

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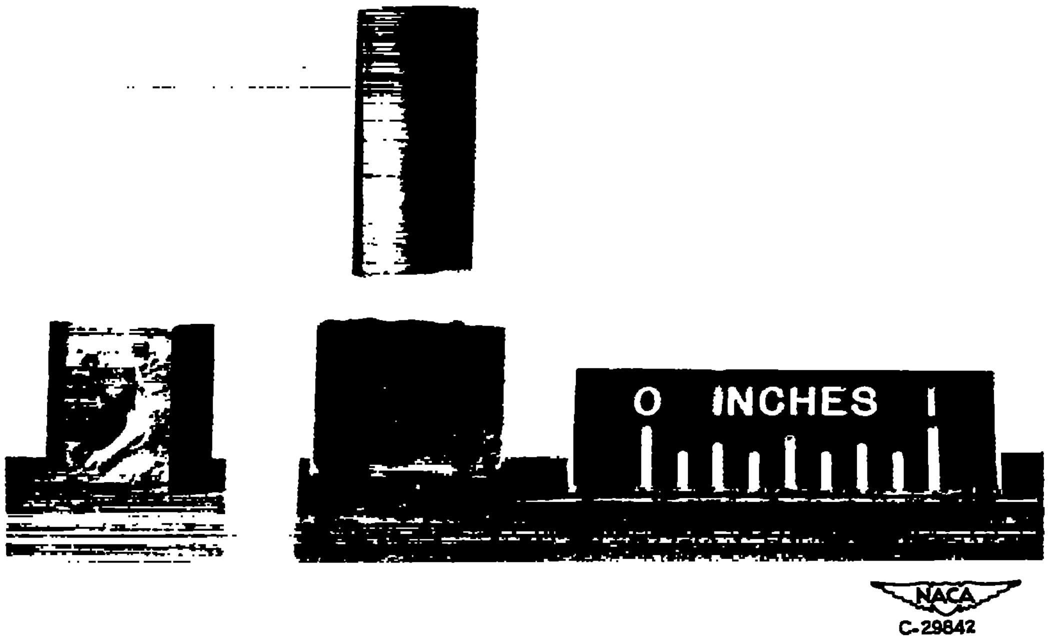


Figure 11. - Failed ceramal blade with cast around root.

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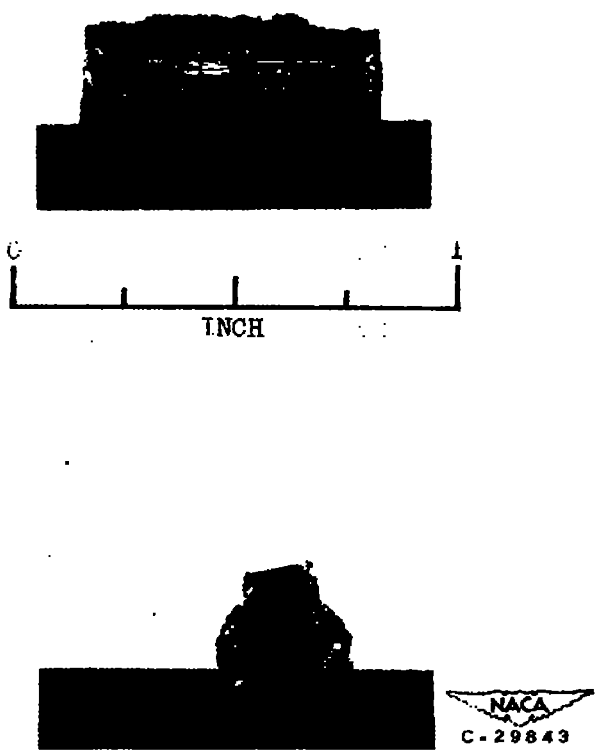


Figure 12. - Failed ceramal blade with enlarged radii and copper insert. Note that failure occurred above neck-roll junction.

[redacted]

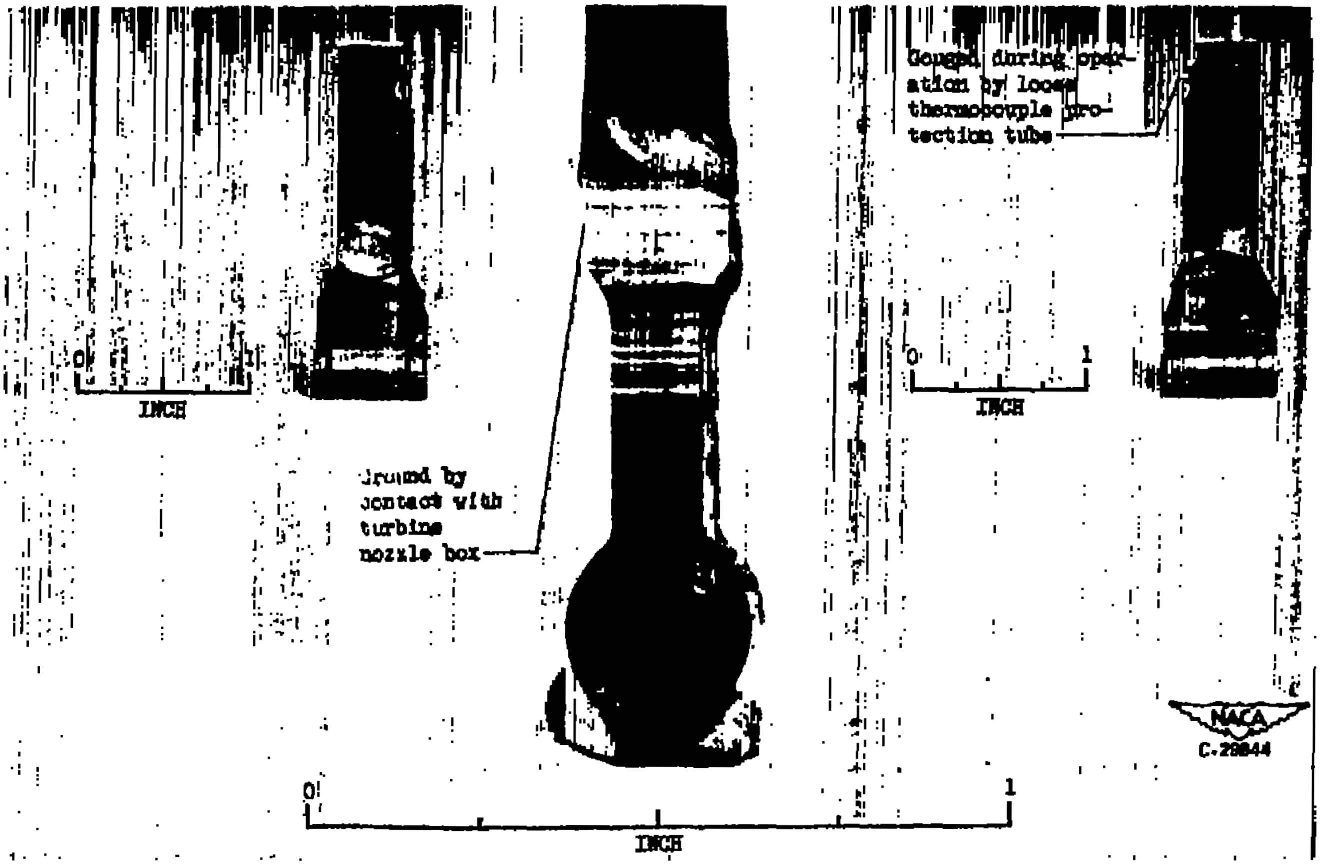


Figure 15. - 20 percent Ni plus 65 percent TiC plus 15 percent (Cb Ta Ti) blade after 99 hours of operation at 1500° F and 25 hours at 1700° F and at 22,850 rpm during which time 100 percent of Stellite 21 and S-816 alloy control sample failed.

[redacted]



[redacted]